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The effect of mountaineering on the association between blood pressure and physical activity: A new multi-sensor ambulatory blood-pressure monitoring device. The Mount Fuji Study

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Abstract

It has not been fully investigated whether the response of blood pressure (BP) to activity at high altitudes differs from that at low altitudes or how temperature is involved in these differences. The author compared BP response to accelerometer measurements during mountaineering and daily living. In 15 healthy people (mean age 33 ± 6 years), a new multi-sensor ambulatory BP monitoring (ABPM) device equipped with barometer, thermometer, and accelerometer was used to measure BP responses to activity during a trip to Mt. Fuji and during daily living. Associations between physical activity (log-transformed 5-min average values of accelerometer just before each ambulatory BP) and the corresponding BP were obtained from 843 and 676 readings during the Mt. Fuji trip and daily living, respectively. All ambulatory systolic BP (SBP) parameters were significantly higher during the Mt. Fuji trip than during daily living (all $p < .01$). There were significant positive correlations between physical activity and corresponding BPs in both mountaineering and daily living (all $p < .01$), and there was an interaction between BPs and physical activity according to the two conditions ($p < .01$). On Mt. Fuji, multivariate regression analysis showed increased physical activity and lower temperature were associated with increased 24-h SBP and diastolic BP (DBP) (all $p < .05$). The goodness-of-fit values of the association between activity and 24-h SBP or DBP were improved by adding temperature to the model of both 24-h SBP and DBP. However, these associations were not found in the daily living model. BP response to activity was more pronounced during mountaineering than daily living.

KEYWORDS
activity, ambulatory blood pressure, high altitude

1 | INTRODUCTION

Exercise is one of the non-pharmacological therapeutics for patients with cardiovascular diseases, hypertension, diabetes, and hyperlipidemia.[1,2] Aerobic exercise is recommended for all patients with cardiovascular disease. Although mountaineering is an aerobic exercise that can be performed at high altitude, there is limited evidence about its safety for patients with cardiovascular disease.[3] At high altitudes, both the temperature and barometric pressure are lower. These environmental changes contribute to an excessive blood pressure (BP) response to exercise.[4,5] As a result, the response of BP to exertion at high altitudes may differ from that during daily living at low altitudes, but these associations have not been fully investigated.

Physical activity is one of the important determinants of BP. Ambulatory blood pressure monitoring (ABPM) is the only kind of BP measurement that can measure the response of BP to activity in daily life. However, there have been few devices that can simultaneously assess physical activity and BP in daily life, and research in this field has not progressed. We recently developed a multi-sensor ABPM system equipped with an accelerometer, a thermometer, and a barometer.[6] With the new capacity of this device to measure BP and physical activity simultaneously, we have proposed a new term to describe reactivity to physical activity: “actisensitivity”.[7] We hypothesized the BP actisensitivity during mountaineering would be increased compared to that in daily living, and we conducted a comparison study using this novel ABPM device to measure BP and activity simultaneously during mountaineering and daily living.

2 | METHODS

The present study was conducted in August of 2017–2019. We enrolled 15 healthy subjects. There were four participants in 2017, six participants in 2018, and five participants in 2019. The novel ABPM device was worn during the climb up and down Mt. Fuji and during daily living including exercise. The ABPM in daily living was performed within 1 week after the Mt. Fuji trip.

2.1 | Climbing Mt. Fuji

Climbing was started from the 5th station of Mt. Fuji of the Yoshida route. Study participants had spent the night at the 5th station of Mt. Fuji, or Fujiyoshida city at the foot of Mt. Fuji. Study participants took 8 h to climb the Yoshida route to the summit of Mt. Fuji and stayed on the summit of Mt. Fuji research station for 15 h overnight. The next day, study participants took 5 h to descend to the 5th station of Mt. Fuji. The altitude of the 5th station of Mt. Fuji of the Yoshida route was 2305 m, and the altitude of the summit of the Mt. Fuji research station was 3776 m (Figure 1).

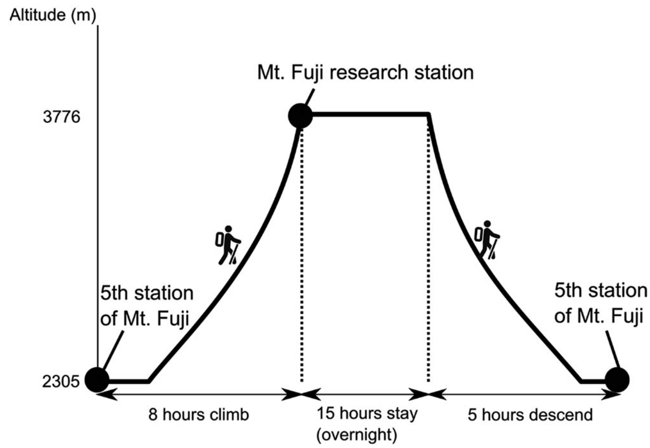

FIGURE 1 Figure of mountaineering Mt. Fuji

2.2 | Measurement by multi-sensor ABPM

Study participants wore the multi-sensor ABPM device (TM-2441; A&D, Tokyo, Japan), which has a barometer, a thermometer, and an accelerometer. BP (by the oscillometric method) and pulse rate (PR) were recorded every 30 min. The temperature and barometric pressure at the time of BP measurement were recorded. This device was validated previously.[6] During the Mt. Fuji trip, ABPM was worn continuously for 28 h (Figure 1), including the sleeping period at the Mt. Fuji research station. Acute mountain sickness (AMS) score was also measured during mountaineering.[8] Concerning ABPM measurement during daily living, participants were instructed to follow their normal daily routine. The participants were doctors and office workers, and the altitudes of their workplaces were within 50–110 m above sea level.

Sleep BP was defined as the average of BP measurements during the time the participant was in bed, and awake BP was defined as the average of BP measurements recorded during the rest of the day.

2.3 | Definition of actisensitivity for BP

Physical activity was measured by a high-sensitive accelerometer which can detect the wearer's physical movements in three directions. The obtained values of physical activity comprised 5-min average values of physical activity just before each BP measurement. Actisensitivity was defined as the slope of the BP changes in response to physical activity. It was calculated as the slope of the correlation line between ambulatory BP values as the vertical axis and the log-transformed 5-min average values of physical activity as the horizontal axis.[9]

2.4 | Statistical analysis

Data are expressed as the means ± SDs or percentages, or as medians (interquartile range). A paired t-test was performed to test mean differences between measurement during mountaineering and daily living.

TABLE 1 Difference in the indexes assessed by ABPM between mountaineering and daily living ($n = 15$)

Variables	Mountaineering	Daily living	p-value
24-h SBP, mmHg	119 ± 6	113 ± 5	<.01
24-h DBP, mmHg	77 ± 5	76 ± 5	.39
24-h PR, bpm	90 ± 10	67 ± 8	<.01
Awake SBP, mmHg	124 ± 9	119 ± 6	.02
Awake DBP, mmHg	82 ± 7	80 ± 7	.37
Awake PR, bpm	95 ± 10	70 ± 9	<.01
Sleep SBP, mmHg	106 ± 8	100 ± 5	<.01
Sleep DBP, mmHg	66 ± 5	63 ± 5	.06
Sleep PR, bpm	79 ± 13	56 ± 11	<.01
Nocturnal BP reduction, %	14.1 ± 8.8	15.9 ± 5.5	.39
Total activity, G	54075 [41976, 71614]	23067 [15136, 29309]	<.01
Mean temperature, °C	23.8 ± 2.1	28.3 ± 2.4	<.01
Mean Barometric pressure, hPa	698 ± 30	1003 ± 8	<.01
AMS score	4.0 ± 2.2	–	
AMS score > 3, n (%)	10 (67)	–	

Abbreviations: ABPM, ambulatory blood pressure monitoring; AMS, acute mountain sickness; BP, blood pressure; DBP, diastolic blood pressure; PR, pulse rate; SBP, systolic blood pressure.
Data are means ± SDs, medians [25%, 75%] or numbers (percentages).

All values of BP, temperature, barometric pressure, and activity that were measured for all 15 participants were used for univariate and multivariate analysis. Pearson's correlation coefficient was calculated by simple correlation analysis. Multivariate linear regression analysis was performed to investigate the factors associated with SBP and DBP. The variables that were significant in univariate analysis were entered into the multivariate model. Linear regression analysis was performed to investigate temperature or barometric pressure to provide a better index of BPs. The improvement of the goodness-of-fit achieved by incrementally adding variables was computed using forced-entry multiple regression analysis. The variables that were significant in the multivariate model were used to investigate the improvement of the goodness-of-fit. In Model 1, the association between activity and BP was assessed. Models 2 and 3 included significant variables for multivariate analyses. Variance inflation factors were calculated to examine the possible existence of substantial multicollinearity among the variables, and values of more than 3.0 were considered to indicate collinearity. Probability (p) values $< .05$ were accepted as significant. All statistical analyses were performed with SPSS software, ver. 26.0 (IBM, Armonk, NY).

3 | RESULTS

Study participants, comprising 12 males and 3 females, had a mean age of 33 ± 6 years. Table 1 shows a comparison of BPs, activities, and some environmental data between mountaineering and daily living. SBP and PR in 24-h, awake, and sleep conditions were significantly higher on the mountaineering than those in daily living at low altitudes. Total activity was significantly higher in the mountains than at low altitudes. Mean temperature and mean barometric pressure were significantly lower in the mountains than in low altitudes. AMS defined by AMS score >3 was observed in 67% of study participants during their time in the mountains.

A total of 843 readings of BP and activity values during the mountaineering and 676 readings during daily living were obtained, and the association between BP and activity was investigated. Figure 2 shows a scatterplot between BP and activity. Activity during both the mountaineering and low-altitude daily living were significantly correlated with SBP and DBP (SBP of mountaineering: R = .26, $p < .01$, SBP of daily living: R = .16, $p < .01$ DBP of mountaineering: R = .18, $p < .01$, DBP of daily living: R = .10, $p = 0{,}01$). There was a significant interaction between actisensitivity of SBP and condition (mountaineering vs. daily living) ($p < .01$). Similarly, there was a significant interaction between actisensitivity of DBP and condition ($p < .01$).

We performed univariate analysis to investigate the factors affecting BP (Table 2). During the mountaineering, temperature, barometric pressure, and activity were significantly associated with 24-h SBP and DBP. However, the AMS score was not associated with 24-h SBP and DBP. Significant variables in univariate analysis were entered into multivariate logistic regression analyses (Table 3). During mountaineering, activity and temperature were independently associated with 24-h SBP (activity: $\beta = .12$, $p < .01$, temperature: $\beta = -.26$, $p < .01$). Activity, temperature, and barometric pressure were independently associated with 24-h DBP (activity: $\beta = .10$, $p = .03$, temperature: $\beta = -.20$, $p < .01$, barometric pressure: $\beta = .13$, $p < .01$). During daily living, activity, and temperature were significantly associated with 24-h SBP, and activity was significantly associated with 24-h DBP in univariate analysis. In

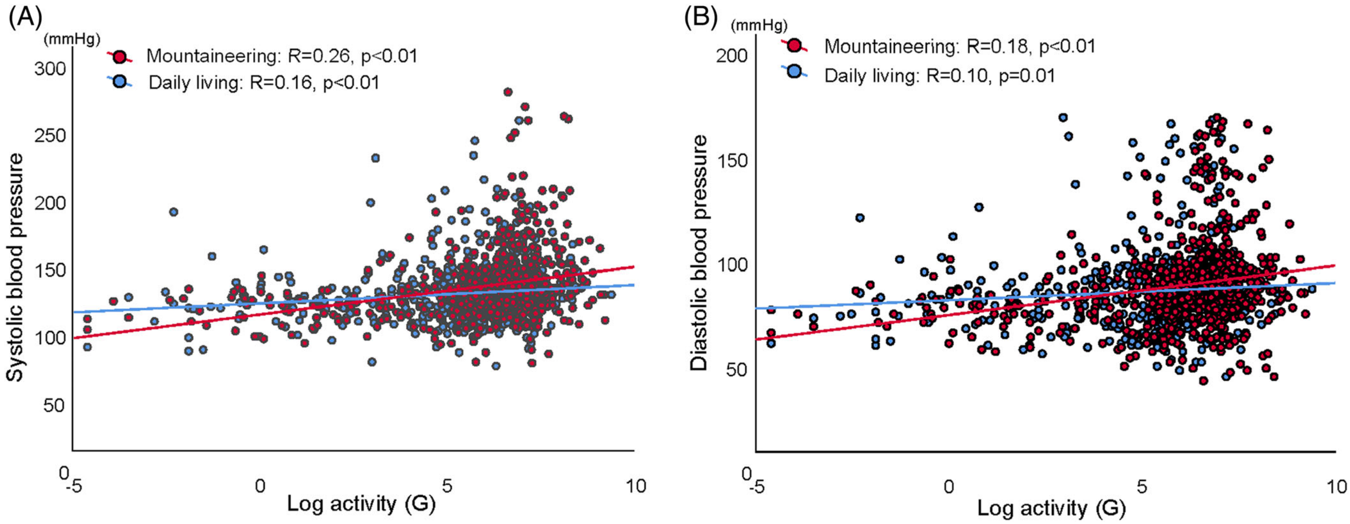

FIGURE 2 The associations between activity during mountaineering and daily living and blood pressures. A: Systolic BP, B: Diastolic BP

TABLE 2 Univariate analysis with 24-h SBP and DBP as dependent factors

	24-h SBP (mmHg)		24-h DBP (mmHg)	
Variables	R	*p*-value	R	*p*-value
Mountaineering				
log activity, G	.29	<.01	.25	<.01
Temperature, °C	−.37	<.01	−.33	<.01
Barometric pressure, hPa	.27	<.01	.29	<.01
AMS score	−.04	.89	−.15	.60
Daily living				
log activity, G	.13	<.01	.09	.04
Temperature, °C	−.10	<.01	−.03	.38
Barometric pressure, hPa	−.06	.10	−.07	.06

Abbreviations: AMS, acute mountain sickness; DBP, diastolic blood pressure; SBP, systolic blood pressure.

TABLE 3 Multiple linear regression analysis with 24-h SBP and DBP as dependent factors

	24-h SBP		24-h DBP	
Variables	*β*	*p*-value	*β*	*p*-value
Mountaineering				
log activity, G	.12	<.01	.10	.03
Temperature, °C	−.26	<.01	−.20	<.01
Barometric pressure, hPa	.07	.14	.13	<.01
Daily living				
log activity, G	.12	<.01	.09	.04
Temperature, °C	−.08	.06	–	–
Barometric pressure, hPa	–	–	–	–

Abbreviations: DBP, diastolic blood pressure; SBP, systolic blood pressure.

multivariate analysis during daily living adjusting for significant variables, activity was significantly associated with 24-h SBP ($\beta = .12$, $p < .01$) and 24-h DBP ($\beta = .09$, $p = .04$).

To investigate whether there was a change in the goodness-of fit of the linear relationship between each BP and activity induced by adding other environmental measures to activity in mountaineering or daily living, we added temperature or barometric pressure in a multiple linear regression model of 24-h SBP and 24-h DBP (Table 4). During mountaineering, the goodness-of-fit of the relationship between 24-h SBP and activity was incrementally improved by adding temperature. With regard to 24-h DBP, adding temperature and barometric pressure improved the goodness-of-fit of the relationship between 24-h DBP and activity. On the other hand, during daily living, adding temperature did not improve the goodness-of-fit of the relationship between 24-h SBP and activity.

4 | DISCUSSION

To our knowledge, this is the first study to show that the condition of activity, that is, mountaineering versus daily living, provided different interactions for the association between BP and activity level assessed by multi-sensor ABPM. Adding the measurements of temperature improved the goodness-of-fit of the association between SBP and activity in the high-altitude data.

The present study showed that both during mountaineering and during low-altitude daily living, activity was associated with BP, but the situation of the activity interacted with the relationship between BP and activity level. Simply put, the rate of increase in BP per the same amount of activity was higher during mountaineering than in daily living. Overall, the amount of activity during mountaineering was greater than that of daily living. Thus, it can be expected that average ambulatory BP levels would be higher during mountaineering than dur-

TABLE 4 Change in the goodness-of-fit of the linear relationship between blood pressure and activity induced by adding temperature and barometric pressure

Model		Standardized *β*	*p*-value	VIF	R^2	Change in R^2	Change in F	*p* value for the change in model
Mountaineering								
24-h SBP								
Model 1	log activity, G	.28	<.01	–	.08	–	–	–
Model 2	log activity, G	.14	<.01	1.32	.14	.06	42	<.01
	Temperature, °C	−.29	<.01	1.32				
24-h DBP								
Model 1	log activity, G	.25	<.01	–	.06	–	–	–
Model 2	log activity, G	.13	<.01	1.32	.11	.05	30.8	<.01
	Temperature, °C	−.25	<.01	1.32				
Model 3	log activity, G	.10	.03	1.39				
	Temperature, °C	−.20	<.01	1.52	.12	.01	7.5	<.01
	Barometric pressure, hPa	.13	<.01	1.39				
Daily living								
24-h SBP								
Model 1	log activity, G	0.13	<.01	–	.02	–	–	–
Model 2	log activity, G	.12	<.01	1.02	.02	.01	3.6	.06
	Temperature, °C	−.08	.06	1.02				

Abbreviations: DBP, diastolic blood pressure; SBP, systolic blood pressure; VIF, variance inflation factor.

ing daily living, simply because of the increased activity. In addition, mountaineering makes it easier to increase BP for activity.

The present study showed that temperature improved the goodness-of-fit of the association between SBP and activity during mountaineering. In addition, temperature and barometric pressure improved the goodness-of-fit of the association between DBP and activity. These findings suggests that activity and environmental condition during mountaineering are each independently associated with BP increase, but that their combination may compound BP increase during mountaineering. Cold temperatures are known to be a determinant of increased BP. Previous reports showed .90 ± .19 mmHg of SBP and .84 ± .15 mmHg of DBP decrease for every 1°C of ambient temperature increase.[10] Temperature decreases by .6°C for every 100 m of altitude increase. The difference in altitude between the trailhead and the summit of Mt. Fuji is 1431 m; the resulting temperature difference could be almost 9°C. Therefore, the temperature, which decreased as the altitude increased, makes BP more sensitive to activity during mountaineering, and resulted in high actisensitivity of BP during mountaineering.

At high altitudes, barometric pressure, temperature, hypoxia, psychological stress, and the autonomic nervous system would all affect BP.[11] It has been shown that acute hypoxia occurs due to systemic vasodilation and pulmonary vasoconstriction, and increases peripheral chemoreceptors and sympathetic nervous system activity.[12–14] Taken together, systemic BP is elevated at high altitudes. With regard to the BP response to exercise at high altitude, a previous study reported that BP response to exercise by cardiopulmonary exercise test was steeper at high altitudes than at sea level.[5] The present study differed from this previous study in that the type of exercise was actual mountaineering, the BP values were measured during the activity rather than afterward, and the altitude also changed during the activities. However, the present study showed that the condition of the activity (barometric pressure and temperature) interacted with the BP response to exercise, and that temperature in particular enhances this relationship.

There are some strengths and limitations in the present study. The strength of this study is that the obtained BP values reflected actual hemodynamic responses during mountaineering because our study was performed during a climb and overnight stay on Mt. Fuji. The limitations were as follows. First, the size of study participants was small. However, measurements were performed upon the same person during mountaineering and daily living. Second, not all factors associated with BP, such as hypoxia, psychological stress, and autonomic nervous activity could be measured because the research equipment we could bring was limited: we could not take blood samples on the summit of Mt. Fuji. Third, the study subjects were all healthy. The response of BP in subjects with hypertension and the influence of antihypertensive drugs were not evaluated. Future research is required to evaluate BP responses during high-altitude mountaineering. Fourth, the temperature obtained by the ABPM device was the temperature near the body surface, not the ambient temperature. However, the temperature near the body surface would directly influence BP regulation. Fifth, there is a difference in the type of activity and altitude between mountaineering and daily living. Further studies are needed whether there is a difference in BP response to activity according to altitude under the condition that the same activity is performed on the ground level and at high altitude.

5 | CONCLUSIONS

The actisensitivity of BP during mountaineering was greater than that of daily living. Temperature was a factor more significantly associated with BP than barometric pressure and compounded the association between activity and BP increase during mountaineering. When people climb mountains, it is important to pay attention to temperature drop to prevent excessive BP variation.

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CONFLICT OF INTEREST

The authors have no conflict of interest.

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